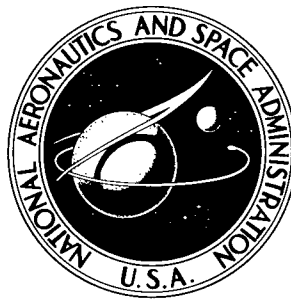


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SURFACE FAILURE OF ALUMINA BALLS
DUE TO REPEATED STRESSES
APPLIED IN ROLLING CONTACT
AT TEMPERATURES TO 2000° F

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SUMMARY

The five-ball fatigue tester was used to study the behavior of alumina balls under repeated stresses applied in rolling contact. Hot-pressed and cold-pressed-and-sintered 1/2-inch alumina balls were tested at 80° and 700° F, maximum Hertz stresses of 250,000 to 650,000 psi, a contact angle of 20°, and a shaft speed of 950 rpm with a mineral oil lubricant.

Failure appearance in alumina was unlike fatigue pits found in bearing steels and a crystallized-glass ceramic. A typical failure was a shallow eroded area approximately 1 mil deep progressing slowly from a very small pit to one spanning the track width. Failure appearance and rate of progression were similar for hot-pressed and cold-pressed-and-sintered alumina.

Tests at 80° F with mineral oil lubrication over a range of stresses show that life varies inversely with stress raised to a power that ranges from 9.4 to 10.8 for the hot-pressed alumina and from 6.0 to 8.1 for cold-pressed-and-sintered alumina. The load capacity of hot-pressed alumina at 80° F was one-fifteenth that of a typical bearing steel, seven times that of cold-pressed-and-sintered alumina, and about 15 percent greater than a crystallized-glass ceramic.

Tests showed that both types of alumina had shorter lives and lower load capacities at a race temperature of 700° F than they did at 80° F; these decreases were attributed to decreased lubricant viscosity with increased temperature. Failure appearance and rate of progression at 700° F were similar to those at 80° F for both hot-pressed and cold-pressed-and-sintered alumina.

Preliminary tests at 2000° F and a maximum Hertz stress of 341,000 psi with molybdenum disulfide (MoS₂)-argon (Ar) mist lubrication indicate that alumina is capable of satisfactory rolling-contact operation under these conditions. The failure appearance of hot-pressed alumina at 2000° F appears to be similar to that at 80° F.

INTRODUCTION

Advancing technology has created a need for reliable bearings that are capable of operating at elevated temperatures for long periods of time. Since many aerospace applications dictate operating temperatures that are beyond the useful range of today's ferrous and nonferrous bearing materials, the more refractory metals and compounds must be considered. Alumina is such a material of interest.

The selection of alumina as a material to be investigated was based on the relatively large amount of information available on its physical properties, which indicates that the material has a high degree of hardness, a high melting point, a high modulus of elasticity, and a high compressive strength. Such properties indicate that alumina has considerable promise as a high-temperature bearing material. Typical values of the physical properties of alumina are shown in the section MATERIALS.

Data reported in references 1 and 2 indicate that, in both sliding and rolling contact at temperatures up to 1200° F, alumina exhibits friction and wear characteristics somewhat similar to those of conventional bearing steels and alloys over the same temperature range.

Fused alumina (96.0 percent Al_2O_3) balls were run unlubricated under oscillatory motion on several plate materials at temperatures from 600° to 1200° F and at maximum Hertz stresses from 637,000 to 1,012,000 psi (ref. 1). The wear in all tests was light, but in some tests at high loads the balls fractured. (Fracture at such severe stresses would not be unexpected.)

The coefficient of friction of alumina sliding unlubricated on several materials at temperatures up to 1600° F is comparable to that of M-2 steel sliding unlubricated on the same materials at temperatures up to 1000° F (ref. 2). Further data reported in reference 2 indicate no essential difference between the friction and wear characteristics of hot-pressed and cold-pressed-and-sintered (hereinafter called cold-pressed) alumina sliding on either M-2 steel at 1000° F or Inconel X at 1600° F.

In view of the reported literature on both the physical properties and the friction and wear properties of alumina, it can be concluded that this material is a candidate bearing material for rolling-element bearings at temperatures of 1600° F (and possibly higher). Thus, the objective of this investigation was to examine the effects of temperature and stress on the surface failure of both hot-pressed and cold-pressed alumina ball specimens under repeated stresses applied in rolling contact. Tests were conducted with 1/2-inch-diameter ball specimens in a five-ball fatigue tester at maximum Hertz stresses of 250,000 to 650,000 psi, a shaft speed of 950 rpm, a contact angle of 20°, and at 80° and 700° F with a highly refined naphthenic mineral oil as the lubricant.

Preliminary rolling-contact tests were also conducted on both types of alumina balls in a modified five-ball tester at 450 rpm and 2000° F with molybdenum disulfide (MoS_2)-argon (Ar) mist lubrication.

The data at 80° F obtained in this investigation are compared with the data for steel ball specimens. All experimental results for a given type of material were obtained with the same batches of material and lubricant.

MATERIALS

Some typical properties of alumina are listed in table I. These properties are not measured properties of particular materials used in these tests.

TABLE I. - TYPICAL PROPERTIES OF ALUMINA (REF. 3)

Property	Temperature, °F	Value
Melting point, °F	-----	3659 to 3723
Vapor pressure, mm Hg	3235	10^{-7}
Mean coefficient of thermal expansion, in./(in.)(°F)	70 to 3875	4.45×10^{-6}
Thermal conductivity, (cal)(cm)/(cm ²)(sec)(°C)	0	0.72
	700	0.033
	2000	0.013
Compressive strength, psi	80	427,000
	752	214,000
	2012	85,000
Tensile strength, psi	80	35,800
	2012	≈32,000
Young's modulus, psi	80	52.4×10^6
	2012	≈41×10 ⁶

In addition to these properties, alumina has good thermal shock resistance, is very hard (9+ on Moh's scale), and is easily obtained in a relatively pure form (>99 percent Al₂O₃). An undesirable property of alumina, however, is its very low ductility.

Both hot-pressed and cold-pressed alumina were selected for this study. The materials were fabricated into rough blanks and finished into 1/2-inch-diameter ball specimens of grade 25 specification (0.000025-in. sphericity, 0.000050-in. uniformity).

Both types of alumina were 99 percent aluminum oxide (Al₂O₃) (according to the manufacturers). As determined by X-ray diffraction at the Lewis Research Center, the trace impurities were chiefly magnesium, silicon, and iron in the

hot-pressed alumina, and magnesium, silicon, and calcium in the cold-pressed alumina. The hot-pressed specimens were gray which is believed to be caused by a complex spinel phase. X-ray diffraction indicates that this complex spinel phase has a composition near that of nickel aluminate ($\text{NiO} \cdot \text{Al}_2\text{O}_3$). The cold-pressed-alumina specimens varied from a nearly pure white to a very light cream color.

Difficulty was encountered in obtaining a good surface finish on the cold-pressed specimens. Many shallow pits as wide as 0.003 inch were observed at a magnification of 15 diameters on the surface of the as-received balls. The number and size of these pits varied among specimens. The surface finish on the hot-pressed specimens was better. Very few pits were observed (at 15 diam) on these specimens; those that were observed were similar in appearance to those on the cold-pressed specimens but smaller in size. Photomicrographs of metallurgically polished cross sections of the two materials are shown in figure 1. The pores in the cold-pressed alumina are larger, which may account for

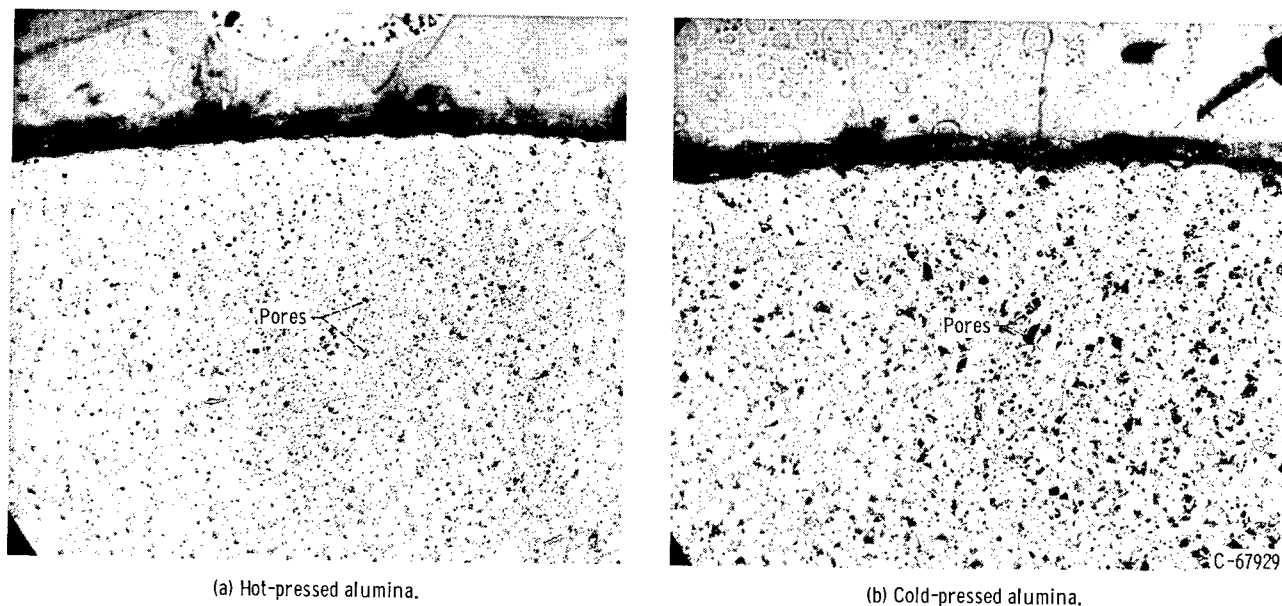


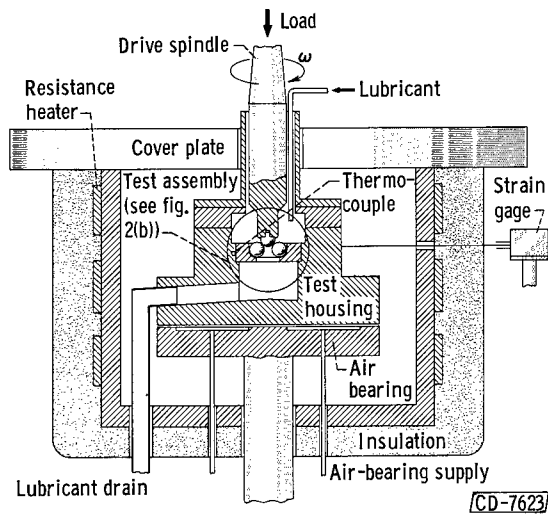
Figure 1. - Photomicrograph of section of alumina ball specimen, X60.

the difference in surface finish. The porosities of the hot- and cold-pressed alumina used in these tests are 0.6 and 4.3 percent, respectively. These values were determined by water-displacement measurements.

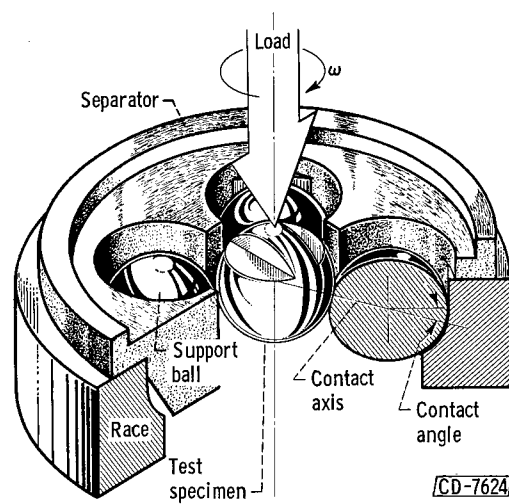
APPARATUS

Five-Ball Fatigue Tester With Air-Bearing Support

The five-ball fatigue tester used in this investigation is described in detail in reference 4. Figure 2(a) is a section view of this tester. The test assembly (fig. 2(b)) consists of a test specimen pyramided on four lower



(a) Section view showing air-bearing support.

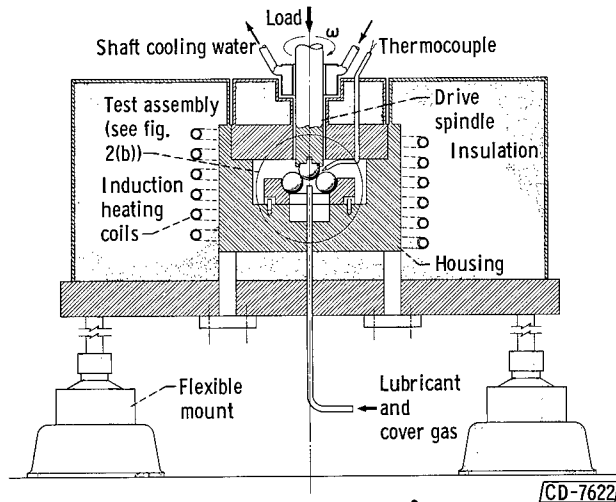


(b) Test assembly.

Figure 2. - Five-ball fatigue tester.

support balls, positioned by a separator and free to rotate in an angular contact raceway. Specimen loading and drive are applied through a vertical spindle that is notched at its lower end to fit a tongue cut in the test specimen. Loading was accomplished by dead weights acting on the spindle through a load arm. Contact load is a function of this load and the contact angle. For every revolution of the drive shaft, the test specimen receives three stress cycles.

The test assembly is supported by an air bearing that permits precise horizontal alinement. The test temperature was measured at the outside diameter of the race and was maintained by electrical resistance elements heating the ambient air. In tests at 80° and 700° F, the ball specimens were lubricated with a highly refined naphthenic mineral oil introduced in mist form. The lubricant mist was heated to test specimen temperature by a resistance heater wrapped around the lubricator tube. The support ball material was 52100 steel for the 80° F tests and M-50 steel for the 700° F tests.



(c) Modified for tests at 2000° F.

Figure 2. - Concluded. Five-ball fatigue tester.

High-Temperature Five-Ball Fatigue Tester

The modified five-ball tester used for the 2000° F tests is shown in figure 2(c). The nickel-base-alloy housing is supported by rods held in flexible rubber mounts. Minor misalignments and vibrations are absorbed by these mounts. Operating temperatures up to 2000° F are maintained by induction heating coils wound around

the test housing. Shaft speeds up to 450 rpm are controlled by a variable-speed drive unit.

Lubrication is accomplished with a dry powder lubricant carried in an inert gas injected into the test assembly. For these tests, MoS₂ powder and high purity argon were used. The support balls were 1/2-inch-diameter, grade 25, hot-pressed alumina. Race and separator materials were cold-pressed alumina and Hastelloy X, respectively.

PROCEDURE

Before testing, the alumina specimens were kept in a clean, dry atmosphere. The cold-pressed specimens were cleaned in an ultrasonic cleaner to remove material left in the surface pits during fabrication. Subsequently, the test specimens were inspected at a magnification of 15 diameters, and the size and the number of initial surface pits in the running track area, if any, were recorded.

At the start of a test, the test specimens and the support balls were coated with lubricant and installed in the test assembly. Loading was subsequently applied, and the test shaft was brought up to operating speed. In the 700° and 2000° F tests, the raceway was heated to operating temperature before the test was started. Periodic inspections of the test-specimen running track were made at a magnification of 15 diameters, and observations were recorded. The time interval between inspections varied with the stress level at which the test was run and with the observed rate of growth of a failure pit. A specimen was considered failed when a pit reached the full width of the running track. The entire test assembly was cleaned and inspected between tests, and new support balls were installed before the start of another test.

RESULTS AND DISCUSSION

Rolling-Contact Life Tests

These tests were conducted with cold- and hot-pressed alumina balls, in the five-ball fatigue tester described previously, at a shaft speed of 950 rpm, a contact angle of 20°, and race temperatures of 80° and 700° F. Step-load tests at the previously stated conditions were made with each material to determine the stresses at which these specimens could be tested to produce a failure within a reasonable time. In order to determine the stress-life relation for alumina, three and four stresses were chosen for the cold- and the hot-pressed materials, respectively. An intermediate stress was chosen for each material for tests at 700° F.

The life data were treated statistically according to the methods of reference 5 and plotted on Weibull coordinates. A straight line was drawn through each array of points by the method of least squares. The results at 80° F are shown in figure 3. The 10- and 50-percent lives are tabulated in table II for both the 80° and 700° F tests. The life data show an expected decrease in life with increasing contact stress.

TABLE II. - LIFE AND LOAD CAPACITY RESULTS WITH HOT-
AND COLD-PRESSED ALUMINA BALL SPECIMENS AT 80°
AND 700° F IN FIVE-BALL FATIGUE TESTER

[Shaft speed, 950 rpm; contact angle,
20°; lubricant, mineral oil.]

Maximum Hertz stress, psi	Race temperature, °F	Ten-percent life, stress cycles	Fifty-percent life, stress cycles	Weibull slope	Ball normal load, lb	Load-capacity, lb
Hot-pressed alumina						
500,000	80	2.3×10^6	5.0×10^6	2.5	24.1	31.3
550,000	↓	.66	1.33	2.7	32.1	28.1
600,000		.50	1.42	1.8	41.8	33.5
650,000		.19	.30	4.0	53.2	31.3
550,000	700	.15	.32	2.6	32.1	17.5
Cold-pressed alumina						
250,000	80	2.05×10^6	7.1×10^6	1.5	3.02	4.32
300,000	↓	.72	1.59	2.3	5.21	4.43
350,000		.27	.48	3.3	8.28	4.30
300,000	700	.052	.21	1.4	5.21	1.20

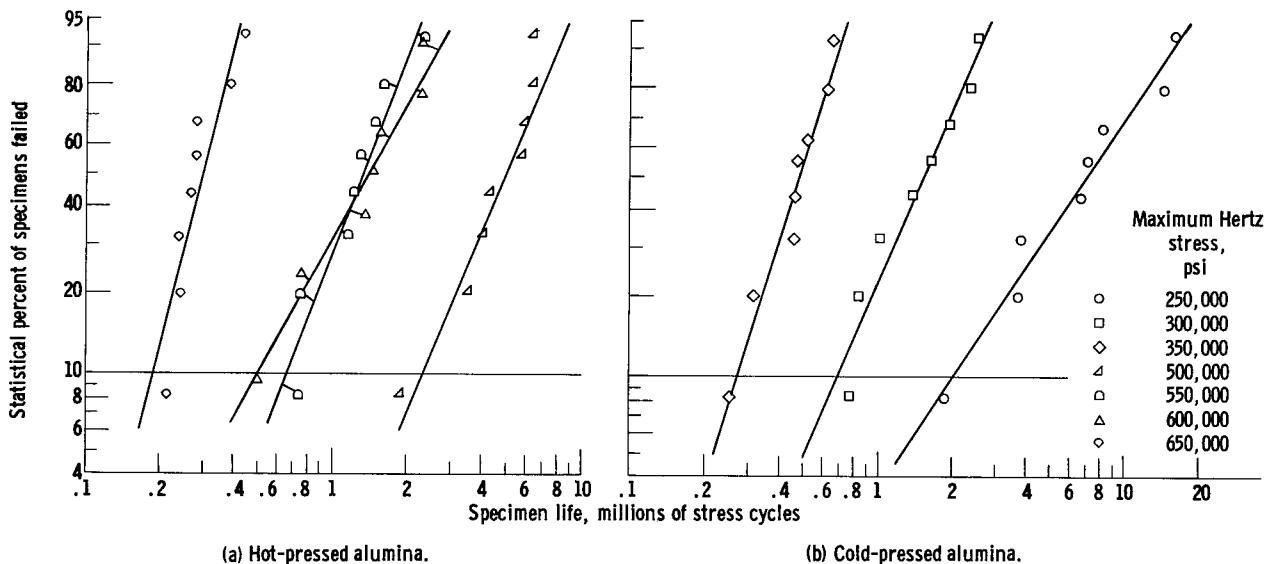


Figure 3. - Rolling-contact life of alumina ball specimens in five-ball fatigue tester. Shaft speed, 950 rpm; contact angle, 20°; race temperature, 80° F; lubricant, mineral oil.

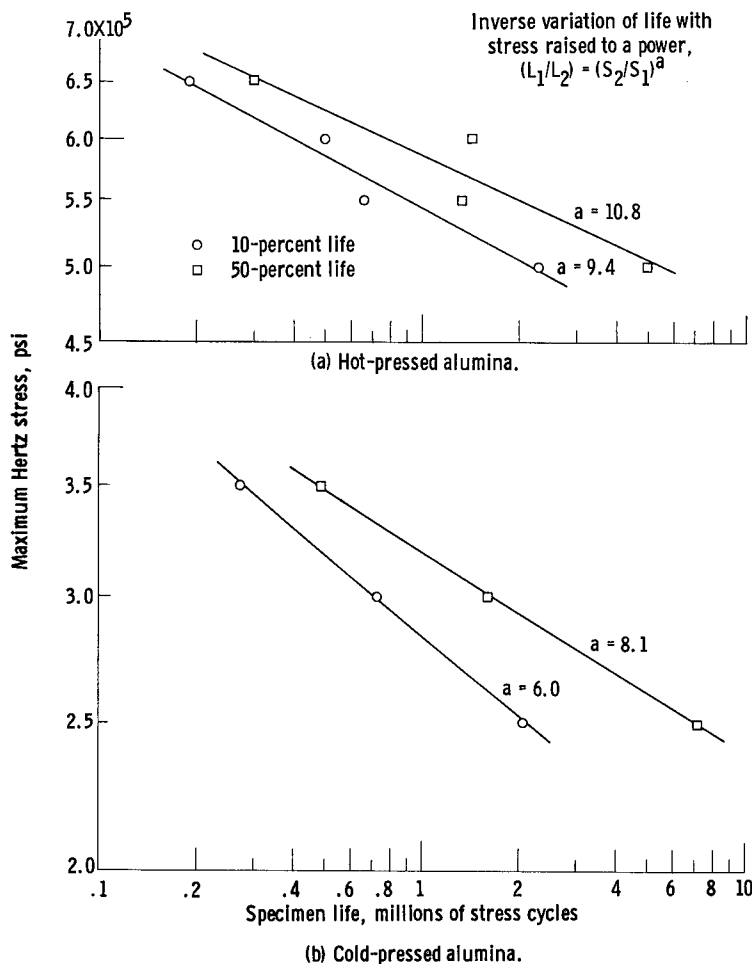


Figure 4. - Stress-life relation of hot- and cold-pressed alumina ball specimens in five-ball fatigue tester. Shaft speed, 950 rpm; contact angle, 20° ; race temperature, 80°F ; lubricant, highly refined naphthenic mineral oil.

Figure 4 are plots of the log of stress against the log of the 10- and 50-percent lives for both hot- and cold-pressed alumina. These plots show that life varies inversely with stress raised to a power ranging from 6.0 to 8.1 for the cold-pressed alumina and from 9.4 to 10.8 for the hot-pressed alumina. (A commonly accepted range for this exponent for bearing steel is from 9 to 10.) Hot-pressed alumina, therefore, shows about the same sensitivity to stress as that which is usually associated with bearing steels. The cold-pressed material appears less sensitive to stress than either the hot-pressed alumina or the bearing steels.

Failure Appearance

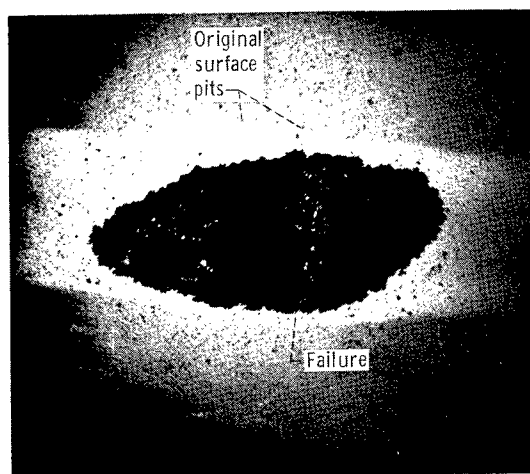
Typical failure pits in alumina test balls are shown in figure 5. These pits were shallow, eroded areas averaging about 1 mil deep and were unlike the deeper

fatigue spalls observed in bearing steels and a crystallized-glass ceramic (ref. 4).

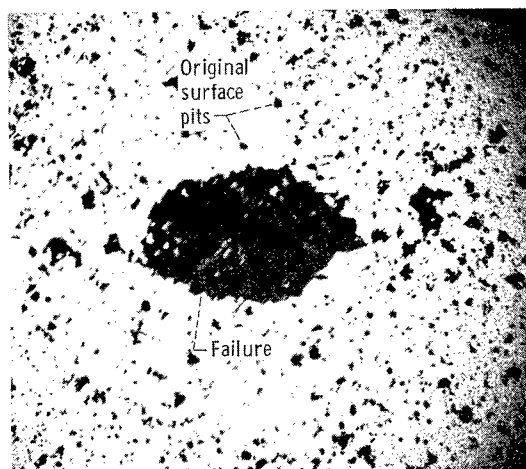
Since the test specimens were inspected periodically during a test, it was possible to observe the progression of the failure pit to full track width. When the failure-pit width was equal to the width of the running track, the test specimen was considered failed, and the test was terminated.

In nearly all tests, the failure started at a small pit in the original ball surface and progressed in size to the full track width. These small pits can be seen in figures 5(a) and (b) in the areas outside the running track. The pits or pores in the original surface of the cold-pressed alumina (fig. 5(b)) were several times larger than those in the hot-pressed alumina (fig. 5(a)).

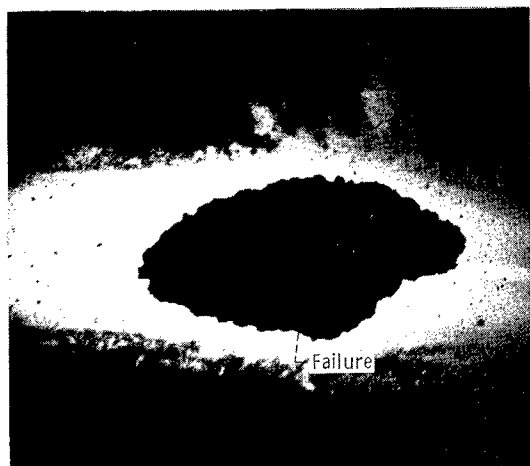
The progression of the pores or pits to full-track-width pits was a slow, erosive process frequently consuming one-half the total running time of the



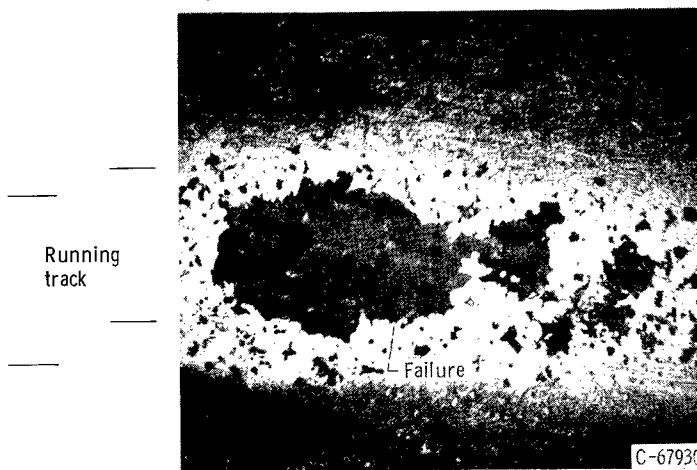
(a) Hot-pressed alumina. Race temperature, 800 F; maximum Hertz stress, 500,000 psi; specimen life, 4.4×10^6 stress cycles.



(b) Cold-pressed alumina. Race temperature, 800 F; maximum Hertz stress, 300,000 psi; specimen life, 2.6×10^6 stress cycles.



(c) Hot-pressed alumina. Race temperature, 700 F; maximum Hertz stress, 550,000 psi; specimen life, 0.24×10^6 stress cycles.



(d) Cold-pressed alumina. Race temperature, 700 F; maximum Hertz stress, 300,000 psi; specimen life, 0.17×10^6 stress cycles.

Figure 5. - Typical failure pit on alumina test ball specimens. X65.

specimen. In nearly every test, several smaller failure pits were at various stages of progression when the largest pit reached the width of the running track.

Failure Mechanism

An examination by light microscopy at 1500 diameters to determine the mode of failure was made of alumina specimens cut transversely through the failure pit. No cracks were observed that would indicate the initiation of fatigue in a manner similar to that for bearing steels. Since both test materials exhibited considerable porosity, the possibility exists that crack propagation over very short distances may occur. The pores in the material under repeated stresses may both initiate and terminate cracks with the result that small

pieces are sporadically lost from an existing surface pit until its size is such that it equals the width of the track. The probability of this type of failure mechanism occurring is supported by the fact that (1) pores or voids exist in both hot- and cold-pressed alumina, (2) initial surface pits exist that eventually grow into failure pits, and (3) growth of the failure pit is a relatively slow process.

Effect of Temperature

One group of specimens of each material was run at a race temperature of 700° F at maximum Hertz stresses of 550,000 and 300,000 psi for hot- and cold-pressed alumina, respectively. The results of these tests are plotted on Weibull coordinates in figure 6. The line shown through the array of points in

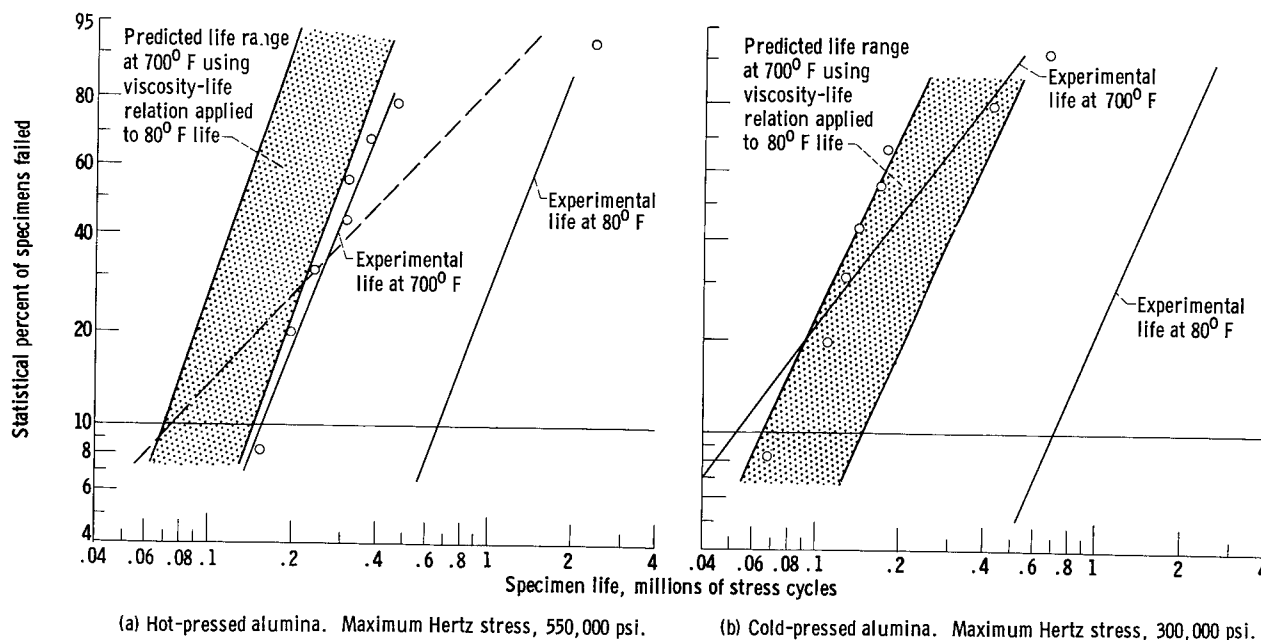


Figure 6. - Effect of 700° F race temperature on life of alumina ball specimens in five-ball fatigue tester. Shaft speed, 950 rpm; contact angle, 20°; lubricant, highly refined naphthenic mineral oil; viscosity at 80° F, 150 centistokes; viscosity at 700° F, 0.6 centistokes.

figure 6(a) does not include the single failure at 2.4×10^6 stress cycles. This data point was considered statistically as a test suspension (ref. 5); however, if this point is included, the line obtained by the method of least squares is the dashed line.

In addition to the experimental life at 700° F, figure 6 shows the experimental life at 80° F (at the same stress) and the predicted life at 700° F. The accepted relation between life L and lubricant viscosity μ is $L = K\mu^n$ where K is a constant and $n = 0.2$ to 0.3 (refs. 6 and 7). If the 80° F life were adjusted to 700° F by the relation

$$\frac{L_{80}}{L_{700}} = \left(\frac{\mu_{80}}{\mu_{700}} \right)^n$$

a life within the range indicated in figure 6 would be expected. The experimental lives at 700° F for both hot- and cold-pressed alumina fall within or close to this predicted range. Although the viscosity-life relation was obtained in fatigue tests with steels where the failures were largely subsurface in origin, the relation appears to apply to the surface-failure life in alumina as well. Thus, the shorter life at 700° F may be accounted for by changes in the viscosity of the lubricant. These results could be expected since the physical properties of alumina do not change appreciably in this temperature range. The appearance of the failure pits in the 700° F tests (figs. 5(c) and (d)) was similar to those at 80° F. The dark material bordering the track in figures 5(c) and (d) is a deposit from the mineral oil lubricant.

Load Capacity

Since the two types of alumina were tested at different stresses, direct comparisons of lives were not made. The two materials are compared on the basis of load capacity, (the contact load in pounds that will produce failure of 10 percent of a group of test specimens in 1 million stress cycles). The experimental capacities of the two materials are tabulated in table II. The capacity of 1/2-inch-diameter hot-pressed alumina balls at 80° F averaged about 31 pounds and that of the cold-pressed alumina balls about 4.3 pounds.

The rolling-contact fatigue life of a typical vacuum melt M-1 bearing steel tested under similar conditions is shown in figure 7 (ref. 8). This

series of steel balls exhibited a load capacity of about 450 pounds. Thus, at 80° F the hot-pressed alumina balls have only one-fifteenth the load capacity of a typical bearing steel and approximately seven times that of cold-pressed alumina. The capacity of hot-pressed alumina at 80° F is about 15 percent greater than that of a crystallized glass ceramic (ref. 4).

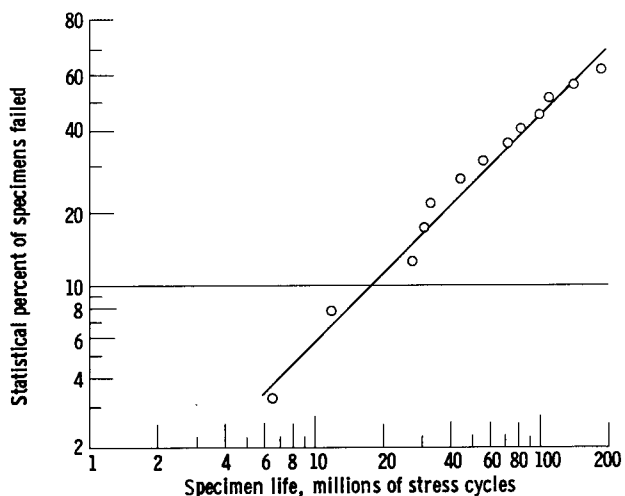


Figure 7. - Rolling-contact fatigue life of AISI M-1 steel ball specimens in five-ball fatigue tester. Shaft speed, 10,000 rpm; contact angle, 20°; race temperature, 145° F; lubricant, synthetic diester; maximum Hertz stress, 800,000 psi; failure index, 13 out of 21 (data from ref. 8).

A decrease in load capacity was observed when the race temperature was increased from 80° to 700° F. This decrease (38- and 73-percent for hot- and cold-pressed alumina, respectively) as previously discussed is believed to result from the decrease in lubricant viscosity due to an increase in temperature.

Rolling-Contact Tests at 2000° F

Several alumina ball specimens were run in a modified five-ball fatigue tester at 2000° F with MoS₂-argon mist lubrication. Tests were performed at a shaft speed of 450 rpm, a contact angle of 20°, and maximum Hertz stresses of 270,000 and 341,000 psi. The results of these tests are shown in table III.

TABLE III. - RESULTS WITH HOT- AND COLD-PRESSED ALUMINA BALL SPECIMENS RUN
AT 2000° F IN MODIFIED FIVE-BALL FATIGUE TESTER

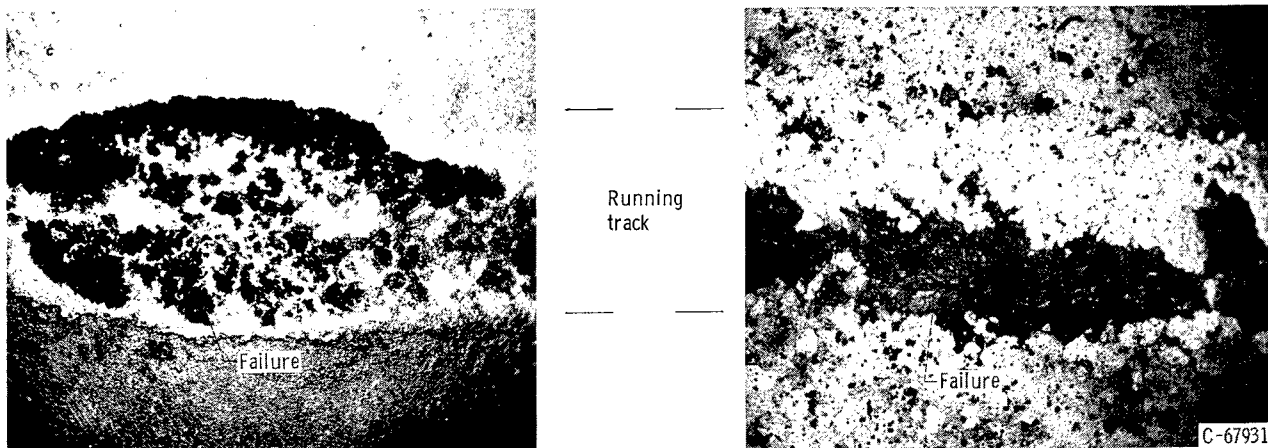
[Shaft speed, 450 rpm; contact angle, 20°; lubrication, molybdenum disulfide-argon mist.]

Test	Test ball material	Maximum Hertz stress, psi	Total stress cycles	Test time, min	Change in surface conditions of track
1	Cold-pressed alumina	270,000	101,000	15	No change.
				45	No change.
				75	Shallow pitting covering about 50 percent of track width in about 15 percent of track length.
2	Hot-pressed alumina	341,000	190,000	60	No change, except for slight polishing of track.
				120	Three pits on track, each covering about 40 percent of track width.
				140	One pit on track, equal to track width (see fig. 8(a)).
3	Cold-pressed alumina	341,000	40,500	30	Shallow pitting covering about 50 percent of track width and about 10 percent of track length (see fig. 8(b)).
4	Hot-pressed alumina	341,000	81,000	60	No change. Several thermal shock cracks in areas near track; test suspended.

The pitting in hot-pressed alumina at 2000° F closely resembled the failure pits produced in the lower temperature tests. Figure 8(a) is a photomicrograph of the pit that occurred in test 2 (table III).

A photomicrograph of a portion of the track of the cold-pressed alumina ball tested under identical conditions (test 3) is shown in figure 8(b). This test was stopped at this point because it was apparent that a general track breakdown was occurring. The failure pit had not yet reached full track width when it became excessively long in the direction of the track. This failure process, also observed in test 1, was unlike that obtained with cold- and hot-pressed alumina at 80° and 700° F or hot-pressed alumina at 2000° F.

As shown in table III, the hot-pressed alumina had been subjected to about five times as many stress cycles as the cold-pressed alumina when the failures occurred. Although both specimens were tested at a maximum Hertz stress of 341,000 psi, the two tests should not be directly compared because of the



(a) Hot-pressed alumina. Maximum Hertz stress, 341,000 psi; specimen life, 0.19×10^6 stress cycles.

(b) Cold-pressed alumina. Maximum Hertz stress, 341,000 psi; specimen life, 0.04×10^6 stress cycles.

Figure 8. - Typical failure pits on alumina ball specimens. Temperature, 2,000° F. X65.

peculiar failure on the cold-pressed specimen.

These limited tests do show, however, that alumina can be operated under rolling-contact conditions at 2000° F. Furthermore, hot-pressed alumina was superior to cold-pressed alumina at 2000° F as well as at lower temperatures. (The number of tests at 2000° F was limited because of the limited number of ball specimens from the same batch of material.)

SUMMARY OF RESULTS

Surface failure tests in rolling contact were conducted with groups of hot- and cold-pressed alumina ball specimens of relatively high purity in the five-ball fatigue tester. These tests were conducted at a contact angle of 20°, a shaft speed of 950 rpm, at race temperatures of 80° and 700° F, at maximum Hertz stresses of 250,000 to 650,000 psi and with a mineral oil lubricant. Support balls were 52100 and M-50 steel in the 80° and 700° F tests, respectively. Preliminary tests were also conducted at 2000° F in a modified five-ball fatigue tester. Both hot- and cold-pressed alumina balls were run to failure at a contact angle of 20°, a shaft speed of 450 rpm, and at maximum Hertz stresses of 270,000 and 341,000 psi with MoS₂-argon mist lubrication. Support balls were 1/2-inch-diameter hot-pressed alumina.

The following results were obtained:

1. The failures in hot- and cold-pressed alumina were very shallow eroded areas approximately 1 mil deep and were unlike fatigue pits found in bearing steels or a crystallized glass ceramic.
2. Progression of an incipient failure to a full-size failure for both the hot- and cold-pressed alumina was a slow process, frequently consuming one-half of the total running time of the specimen.

3. The load-carrying capacity at 80° F of hot-pressed alumina balls is seven times greater than that of cold-pressed alumina. The capacity of the hot-pressed alumina balls is about one-fifteenth that of M-1 bearing steel balls tested under similar conditions.

4. Increasing the race temperature from 80° to 700° F resulted in a reduction in capacity for the hot- and cold-pressed alumina of 38 and 73 percent, respectively. The reduction was attributed to the decrease in viscosity of the lubricating fluid at the elevated temperature. Failure appearance at 700° F was similar to that at room temperature for both the hot- and cold-pressed alumina.

5. The life of hot-pressed alumina at 80° F with mineral oil lubrication varied inversely with stress raised to a power that ranges from 9.4 to 10.8 exhibiting about the same stress-life sensitivity as that for bearing steels; in contrast, the life of cold-pressed alumina was found to vary inversely with stress raised to a power that ranges from 6.0 to 8.1.

6. Preliminary tests at 2000° F and a maximum Hertz stress of 341,000 psi with molybdenum disulfide-argon mist lubrication indicate that alumina is capable of satisfactory rolling-contact operation under these conditions.

7. The failure appearance in hot-pressed alumina at 2000° F was similar to that at 80° F.

Lewis Research Center

National Aeronautics and Space Administration

Cleveland, Ohio, February 13, 1964

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NASA TN D-2274

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